

WAVELET ANALYSIS OF CERAMIC SURFACE IMAGES AS A METHOD FOR MEASURING THE SIZE OF STRUCTURAL ELEMENTS

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The problem of the possibility of visualizing multiscale phenomena developing on the surface of a ceramic material, which is characterized by a high dispersion of structural elements, is important for modern materials science. The relevance of using wavelet analysis to visualize and measure the structural elements of the surface of ceramic samples is shown. The experimental results of processing images of the surface of samples using wavelet analysis are presented. Examples of applying the wavelet transform to the study of model “chessboard” images with simple geometry and precisely known sizes of structural elements are observed. A relation that relates the particle size to the scale parameter of the wavelet spectrum is derived. A simple method for recording and quantifying the structural changes occurring in highly dispersed ceramic samples under the influence of a microwave field is proposed. The effect of reducing the size of structural elements (particles) of the surface of such ceramic samples influenced by microwave radiation by an average of 20% is discovered. The surface of such samples becomes more uniform, which is extremely promising for the development of technology for producing finely dispersed ceramic materials.

Keywords: wavelet spectrum, scale parameter, model, optical image, visualization, structural element, ceramic surface.

Introduction. When studying the structure and surface morphology of any materials, information about the dispersion and periodicity of structural elements, the nature of their distribution, and scale invariance is used. The surface of ceramic samples is extremely irregular, and statistical methods should be used to describe its geometric properties.

The implementation of known methods of surface investigation, such as speckle analysis, profilometry, ellipsometry, electron and atomic force microscopy, requires usage of expensive equipment and special long-term preparation of samples, during which these samples are disturbed. The structure of ceramics can be described by means of digital processing of surface images. In digital processing, the brightness characteristics of signals obtained by various methods are analyzed. Wavelet analysis is one of the modern methods of a systematic approach to signal processing, including optical signals, depending on both temporal and spatial coordinates. In contrast to the Fourier transform, traditionally used for signal analysis, the wavelet transform provides a two-dimensional presentation of the investigated one-dimensional signal. As a result, the pattern of the wavelet spectrograms makes it possible to estimate not only the sizes, but also the spatial distribution of the structural elements of the investigated surface.

The method of wavelet analysis has proven itself in the quantitative description of the topographic structure of dispersed nanomaterials [1]. With the help of wavelet analysis, it is possible to determine the degree of uniformity and ordering of structural elements, substructures of various scales, to evaluate their characteristic sizes and localization. There are known examples of the use of wavelet transform to determine the surface roughness, thickness and wetting angle of a powder-firing coating, the evolution of the morphology of dispersed particles of clay minerals under microwave influence, and also when

analyzing microsections images [2–5]. The possibility of using the continuous wavelet transform to determine particle sizes in real monomorphic disperse systems (homogeneous clay powders) was shown in [6] and the error in determining the equivalent particle diameters in the micrometer region was $\pm 10\%$.

The wavelet transform is based on the decomposition of the signal into special functions as a result of large-scale changes and transfers. Wavelets are special dependencies in the form of short waves with a zero integral value and localization along the time (coordinate) axis, capable of displacement along this axis and scaling (extension-compression). The result of a wavelet transform of a one-dimensional series is a two-dimensional array of amplitudes, i.e., the values of the coefficients $W(a, b)$, where a and b are the parameters of the basic wavelet scale and its shift along the image, respectively. The localization or distribution of these values in the spatial or temporal scales (a, b), called the spectrum of wavelet transform coefficients or the wavelet spectrum, makes it possible to detect changes in the relative contributions of various signal components. At the same time, at different levels of signal decomposition (resolution), two different scales are distinguished. At the top of the spectrogram the scale is approximating, coarse, with a rather slow spatial dynamics of changes and below there is a detailed scale value with local and fast dynamics of changes [7]. By the pattern of the wavelet spectrum, it is possible to estimate the surface structural elements of condensed media and their localization [8].

In scientific research related to the creation of functional materials, investigation of the effects of electromagnetic fields of various frequency ranges on the processes of structure formation has a considerable importance. At present, one of the fundamental problems of studying the ceramics sintering in a microwave field is the identification of structural changes that occur under a specific “non-thermal” effect. A very important aspect of modern materials science is the problem of the possibility of visualizing multiscale phenomena developing on the surface of a ceramic material, which is characterized by a high dispersion of structural elements.

The purpose of this work is to validate the appropriateness of applying the wavelet transform of digital images of the surface of ceramic samples to visualize and investigate the structural transformations occurring as a result of microwave exposure.

Investigated object and registration methods. The surfaces of samples in the form of a disk with a diameter of 25 mm and a height of 10 mm made from kaolin clay by semi-dry pressing method (batch S0) were investigated. Samples molded from dispersed particles of $d \leq 40 \mu\text{m}$ in size were influenced by the microwave field by sequential five-minute exposures at an average radiation power of 300, 600, and 800 W (batch S1).

Images of the samples surfaces were obtained using an optical standard microscope with a high resolution digital ocular in the magnification range of $10\text{--}1000\times$. Using the ImageJ program, surface profiles in the form of a dependence of the intensity of the points of a digital image on the spatial coordinate were obtained. The wavelet analysis of the obtained profiles was carried out using the Wave Toolbo computing package of MATLAB.

According to the definition in [8], the wavelet spectrum is an integral of the product of the wavelet generating function $\psi(a, b)$ and the signal $y(x)$:

$$W(a, b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} y(x) \psi\left(\frac{x-b}{a}\right) dx.$$

The choice of the analyzing wavelet is specified by the type of information that is planned to be obtained from the signal. The following characteristics are decisive when choosing: number of zero moments, media size and smoothness. Each wavelet has specific features in time and frequency spaces, therefore, by varying sets of functions, it is possible to more fully identify and emphasize the desired properties of the analyzed signal. Disturbances of the signals smoothness are detected by vertical stripes, peak values of the signals are marked by maximums, and troughs – by the minimums of wavelet coefficients. Wavelets of odd type more sharply react to jumps and fast changes in signals, marking them with maxima or minima depending on the sign of the differentials. The sharper the features of the signals are expressed, the more they are distinguished in the spectrograms [9].

Among wavelets, the basis stemming from the well localized in the time and frequency domains Morlaix complex wavelet with a central frequency ω_0 is most commonly used:

$$\psi(t) = \exp(i\omega_0 t) \exp(-t^2/2).$$

Results of experimental studies. A wide range of potential applications of the wavelet method of image processing (WTMM) in fundamental and applied sciences was shown in [10]. Similar as in [10], at the first stage of this work a quantitative

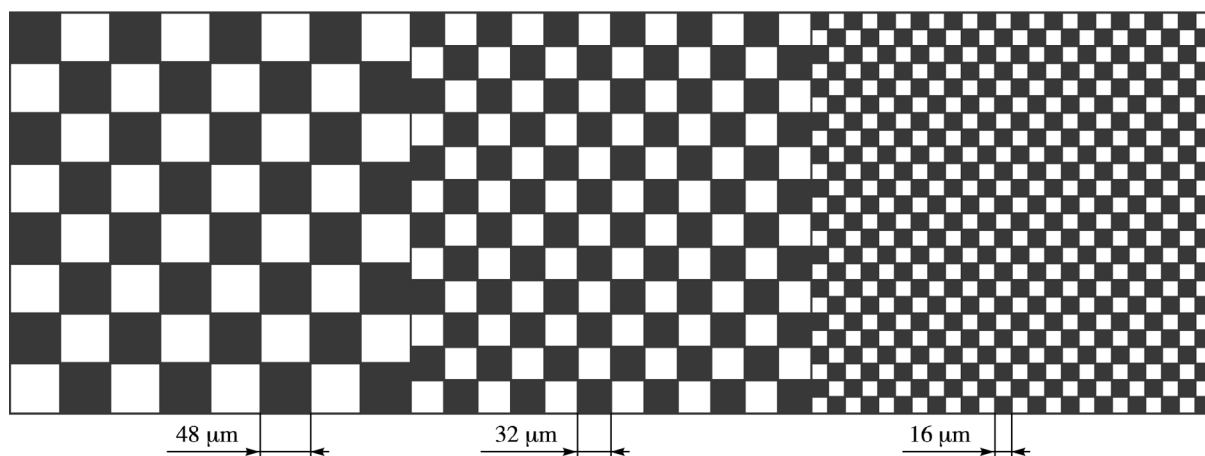


Fig. 1. Simulated image of a “chessboard” surface with different sizes of the sides of the squares.

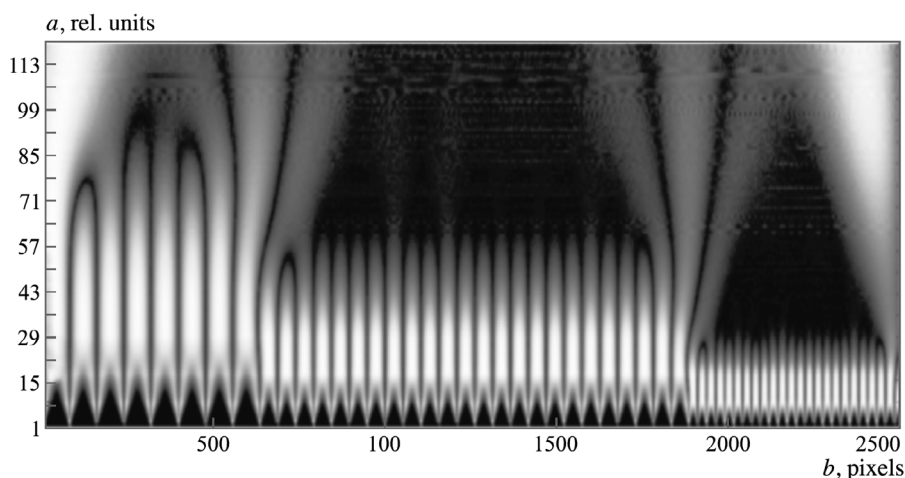


Fig. 2. Wavelet spectrum of a “chessboard” surface.

relationship between the parameters of the wavelet spectra and the structural elements of the digital image was sought in order to visualize and measure the structural elements on the surface of condensed media. To solve this problem, a “chessboard” model surface with simple geometry and precisely known sizes of structural elements was generated. In the direction of the surface cross section (Fig. 1), the sizes of the sides of the squares were 48, 32, and 16 μm . The squares represent well the equiaxial fragmental shape of the particles of samples from kaolin clay. The sizes of the sides of the squares – models of structural elements – were chosen in accordance with the sizes of the real initial particles (about 40 μm). As a result of microwave exposure, morphological changes, which are almost impossible to detect using other methods, can occur in the samples. Such changes include, for example, mesostructural rearrangements associated with the processes of agglomeration and dispersion (an increase or decrease in the size of structural elements, respectively).

Further, cross-sectional profiles were obtained for the generated images, i.e., the dependences of the “brightness” of the digital image points on the spatial coordinate. In Fig. 2 the wavelet spectrum of a “chessboard” surface is shown. The image surface profile consists of structural elements of different scales, varying along the cross section. In Fig. 2 repeating elements of the same type, the so-called “arches” with black boundaries and a light middle [5, 11, 12], can be seen. The sizes of the squares (see Fig. 1) obviously correlate with the height of the vertices of the arches in the wavelet spectrogram (see Fig. 2); therefore, the sizes of the structural elements of the surface image can be determined by measuring the “height” of the arches. Averaging the values of the scale parameter a at the level of the vertices of the arches, the scale parameters along the cross sections of 95,

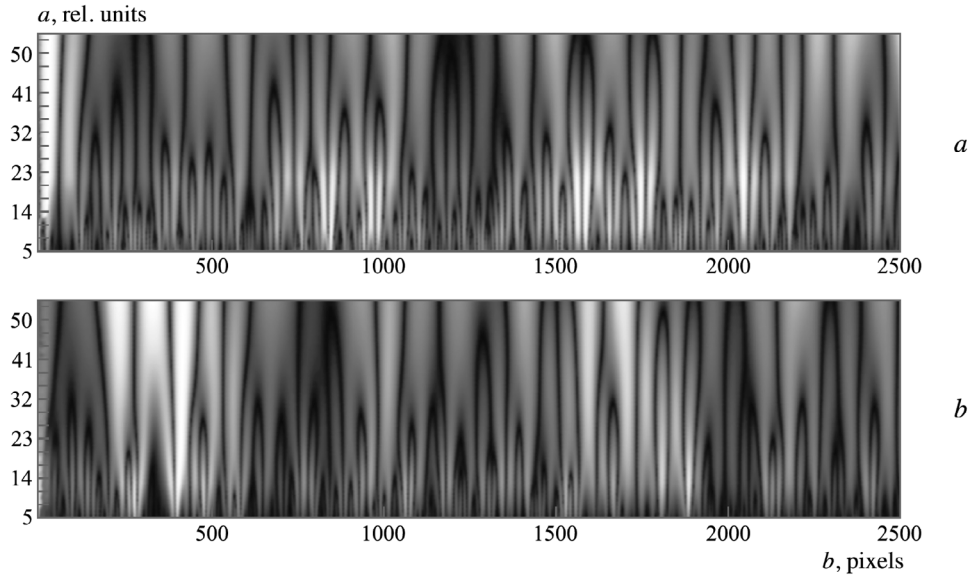


Fig. 3. Typical patterns of the wavelet coefficients of the cross-section of surfaces images of ceramic samples S0 (a) and S1 (b).

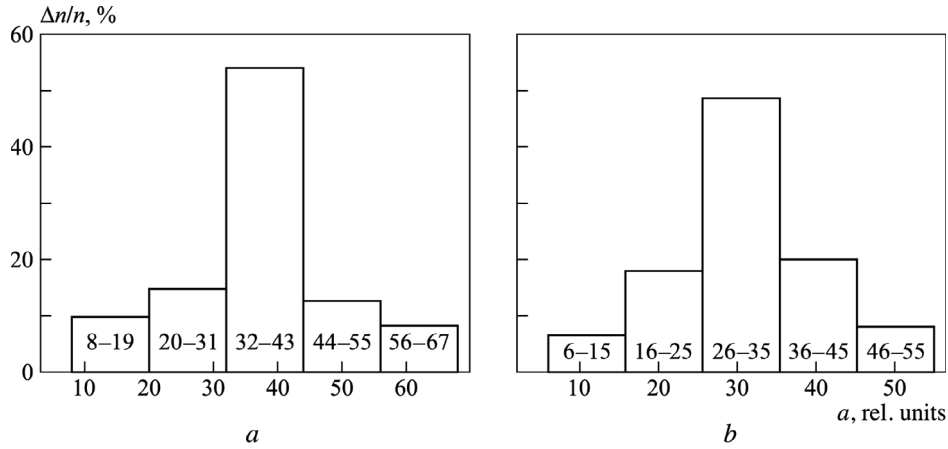


Fig. 4. Frequency distributions of the values of the scale parameter a for surface images of ceramic samples S0 before (a) and S1 after (b) microwave exposure to samples.

63, and 31 μm for the sizes of the sides of the squares 48, 32, and 16 μm , respectively, were obtained. The size R of the squares as structural elements is related to the scale parameter a for the average level of the vertices of arches by the relation

$$R = Ka, \quad (1)$$

where K is the model transformation coefficient.

The model coefficient depends on the magnification of the microscope and the frame size. In this case, when the image size of the model surface was 2000 μm (2500 pixels), the coefficient was $K = 0.506 \mu\text{m}$. Consequently, the average sizes of elements vary in the ranges of $48.3 \pm 0.3 \mu\text{m}$, $31.9 \pm 0.1 \mu\text{m}$, and $15.7 \pm 0.3 \mu\text{m}$, coinciding with the sizes of the “chessboard” squares.

At the final stage, images of the surfaces of samples of kaolin ceramics in the initial state (S0) and after microwave exposure (S1) were investigated. 100 sections were taken from images of sample surfaces. In Fig. 3 wavelet visualization of one section for both samples is presented as a visual example. For each of the sections, the values of the scale parameter a at the level of the vertices of the arches were determined. The ranges of values of parameter a for samples S0 and S1 are 8–67 relative units and 6–55 relative units, respectively (Fig. 4). The sizes of the structural blocks of sample S1 are more uniform

than sample S0. The average values of the scale parameter a at the level of the vertices of the arches are 36.6 ± 0.1 relative units and 29.1 ± 0.1 relative units for samples S0 and S1, respectively.

The sizes R of the structural elements of the samples surfaces were calculated using average values of a and Eq. (1). For samples S0 and S1, R was $18.5 \pm 0.5 \mu\text{m}$ and $14.7 \pm 0.5 \mu\text{m}$, respectively. The sizes of the structural elements (particles) of the samples surface influenced by microwave radiation decreases by an average of 20%; the surface becomes more uniform. The effect of a decrease in the size of structural elements during microwave exposure appears apparently due to the processes of dispersion (cracking, defragmentation) of particles as a result of relaxation of mechanical stresses remaining after the formation of the samples.

Conclusions. The highly informative wavelet analysis method is advisable to use when measuring the structural elements of the ceramic surface. The method allows registration and quantitative estimation of the structural changes occurring in ceramic samples under the influence of a microwave field. The proposed formula for determining the sizes of real structural elements allows relating the scale parameter for the average level of the vertices of the arches in the wavelet spectrum with the sizes of the real structural elements of the surface of the ceramic sample. Using wavelet analysis of optical images of the surface, it was found that microwave heating of ceramic samples made from kaolin clay allows the formation of a more uniform mesostructure with structural elements of reduced size.

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